COMPRESSION TEST OF ALUMINIUM AT HIGH TEMPERATURE

A THESIS SUBMITTED IN PARTIAL FULFILMENT

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By

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National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that thesis entitled, "COMPRESSION TEST OF ALUMINIUM AT HIGH TEMPERATURE" submitted by Mr. TAPAN KUMAR HALDIGUNDI in partial fulfillment of the requirements for the award of *Bachelor of Technology* Degree in Mechanical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter included in this thesis has not been submitted to any other university/ institute for award of any Degree or Diploma.

Date: 10th may, 2012

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ABSTRACT

Compression test of aluminum alloy at high temperature were experimentally carried out on universal testing machine at specified temperatures ranging from 35^{o}C (room temperature) to 225^{o}C and under a constant strain rate of 0.001/s using powdered graphite mixed with machine oil as lubricant throughout the tests. True Stress and strain values were calculated using the engineering equation, which were used to plot the true stress-strain curve for different temperatures, which indicates the mechanical properties of the metal for industrial applications. A common characteristic equation considering true stress, true strain and temperature has been found out using regression analysis .Generalized characteristic equations for each temperature have also been developed by regression analysis, which indicates that the strain hardening exponent first increases, then decreases with increasing temperature, while strength coefficient decreases with increase in temperature.

Keywords—Compression, High Temperature, True Stress, True Strain, Regression Analysis

CONTENT

Chapter 1
Introduction

1. <u>INTRODUCTION</u>

1.1 Compression Test

The use of any material or alloy in a specific fabrication operation is subjected to various parameters related to them. Thorough assessment of these parameters and the corresponding behavior of the materials and resulting properties for the operating conditions need to be analysed properly. Various thermo-mechanical treatments are to be conducted before these alloys undergo different industrial applications. Compression Tests are of extremely high commercial importance, because it helps determining different material properties pertaining to hot as well as cold metal forging employed in a number of metal forming applications. It becomes important to determine suitable load to carry out the operations. Load depends on the flow stress of materials, friction at the tool-workpiece interface and the geometry of the die. Therefore, prediction of hot deformation behavior correlating process variable such as strain, strain rate and temperature to the flow stress of the deforming materials is necessary.

Flow behavior of different alloys at various temperatures can be determined by establishing a relationship among flow stress, strain, strain rate and temperature. So compression tests need to be conducted for a wide variety of strain rates and temperatures. The experimental stress strain data can then be employed to relate true stress, true strain,strain rate & temperature. This relation can then be crosschecked with other experimental data generated.

When a simple compressive load is applied on a particular specimen, the following types of deformation may take place: elastic or plastic compression as in the case of ductile materials, crushing and fracture in brittle materials, or a sudden bending deformation called buckling in long, slender bars, or a combination of these. Ductile materials, such as aluminium lack compressive strength. So lateral expansion and thus an increasing cross-sectional area along with axial shortening takes place. The specimen won’t break, rather excessive deformation occurs instead of loss of strength demonstrating failure characteristics. This behaviour is demonstrated in the figure below.

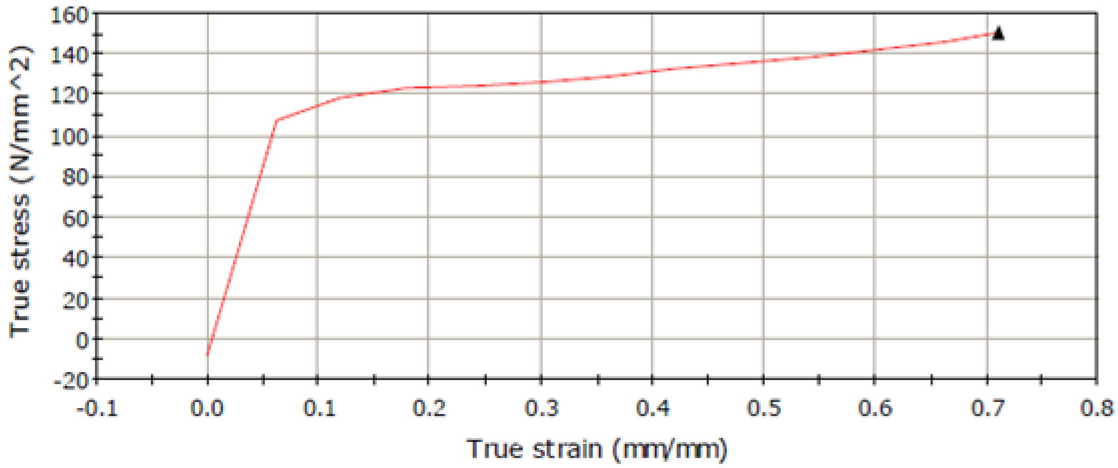

fig 1.1 (flow stress-strain curve for compression test)

1.2 Standard for Compression

In order that test results may be compared easily, the dimensions of test specimens and the methods of applying loads are standardized. One of the major standards organizations is the *American society for Testing and Materials* (ASTM), a national technical society that publishes specifications and standards for materials and testing. Other standardizing organizations are the *American Standards Association* (ASA) and *Bureau of Indian Standard*. For compression testing of aluminium cylinders and foils, ASTM-E9 standard is adopted.

1.3 Effect of Different Parameters on Compression

1.3.1 Effects of Temperature

Increasing temperature generally has the following effects on stress strain curves:

a. It raises ductility and toughness, and

b. It lowers the yield stress and modulus of elasticity

Temperature also affects the strain hardening exponent of most metals.

1.3.2 Effect of strain rate

The rate at which strain is applied to a specimen can have an important influence on the flow stress. Strain rate is defined as : $\text{strain rate} = \frac{\partial \mathcal{E}}{\partial t}$

It is conventionally expressed in units of sec^{-1} i.e. per second. Generally, increasing strain rate increases flow stress. Moreover, the strain rate dependence of strength increases with increasing temperature. The true strain rate is given by

$$\frac{d\mathcal{E}}{dt} = \frac{d(\ln\left({h}/{ho}\right))}{dt} = \frac{1}{h} \times \frac{dh}{dt} = \frac{v}{h} \qquad (1)$$

Where *v* is the crosshead velocity

h is the final height of specimen

ho is the initial height of specimen

The above equation indicates that for a constant crosshead speed the true strain rate will increase as the specimen length decreases. So in order to make true strain rate constant, crosshead velocity should be decrease with decrease in specimen height.

1.4 MATERIAL USED -**Aluminium** (or **aluminum)**

It is a silvery white and ductile member belonging to the boron group of chemical elements. Its symbol is **Al** and its atomic number is 13. It is insoluble in water under normal circumstances. Aluminium is highly reactive chemically to occur in nature as a free metal. Instead, it is found combined in more than 270 different minerals. The primary source of aluminium is bauxite ore.

Aluminum alloys are alloys in which aluminum (Al) is the predominant metal. Commercial purity of aluminum is 99.5 to 99.79%, but pure aluminum is too soft to be of structural value. The primary reason for alloying aluminum is to increase strength without significantly increasing weight. Other reasons are to improve machinability, weldability, surface appearance and corrosion resistance. The typical alloying elements are copper, magnesium, manganese, silicon, and zinc.

- **Properties of Al**

Aluminium is unique and unbeatable combination of properties making its use versatile.It is highly usable and attractive construction material.

Weight: Al is the light material compare to other material like steel. Its Density is 2.700 kg/m^3

Strength: Aluminium is strong with the tensile strength 70 to 700 MPa .its strength depends on the alloying materials and manufacture process.

Elasticity: The Young’s modulus of Al is one-third of steel (E = 70,000 MPa).

Formability: Aluminium has the good formability characteristic ,that may be used to the form in extrusion. Aluminium may also be cast, drawn and milled.

Machinability: Aluminium is very simple to machine. Ordinary machining equipments may be used such as saws and drills. Al is also suitable for forming (both hot and cold process) .

Joining: Aluminium may be joined applying all the normal methods available as the welding, soldering, Adhesive bonding and riveting.

Corrosion resistance: A thin layer of oxide is formed when Al is in contact with air, which provides good protection against the corrosion in the corrosive environment . Its layer may also be given further strength by surface treatment such the powder coating.

Conductivity: Its thermal and electrical conductivities are good compared with copper. Furthermore Al conductor is only half the weight of an equivalent Cu conductor.

Linear expansion: Aluminium has relatively higher coefficient of linear expansion compared to other metals. This shall take into account the design stage of the compensate for difference in the expansion.

Non toxic: Aluminium is not poisonous; therefore it is highly suitable for the preparing and storage of the meal

Reflectivity: Aluminium is the best reflector of the light and heat. Its reflectivity is very high.

- **Applications:**

Aluminum alloy has wide range of application. Followings are some of them.

I. In aircraft and other aerospace structures

II. for boat and shipbuilding, and other marine and salt-water sensitive shore applications

III. for cycling frames and components

IV. for automotive body panels

V. As a packaging materials.

VI. In making household components etc.

CHAPTER 2
LITERATURE SURVEY

2 Literature Survey

Because of widespread use of aluminium in electrical conductors, radiator fin material, air conditioning units, optical and light reflectors and foil and packaging materials, the high temperature behavior of aluminium is essential to know. So to know about it various literatures have been reviewed. Out of them some important literatures are discussed here:

Jin Nengping. et.al. [1], showed that, the peak stress level of 7150 aluminum alloy decreases with increasing deformation temperature and decreasing strain rate. The deformed structures exhibit elongated grains with serrations developed in the grain boundaries Dynamic recovery and recrystalization are the main reasons for the flow softening at low Z value. Zhang Hui et.al. [2], found out that, the true stress strain curves of Al-Mg-Si-Cu aluminum alloy exhibit a peak stress at a small strain, after which flow stress decrease monotonically until high strain. The substructure in the deformed specimens consists of very small amount and fine precipitates with equaxied polygonized subgrains in the elongated grains and developed serrations in the grain boundaries. Xiu-yu WEI. et.al. [3], concluded that, the flow stress of 2197 Al-Li alloy decreases with the increase of deformation temperature and increases with the increase of strain rate. The peak flow stress during high temperature deformation can be represented by *Z* parameter in a hyperbolic sine function.

Aluko O. et.al. [4], found out that the compression curves of aluminum alloy obtained using the barrel correction factor method and the Bridgman re-machining technique (no barreling allowed during the test) are found to have close values, even at higher temperatures. The true-stress versus true-strain curves and the barrel sizes obtained follow empirical power laws, even at higher test temperatures. Chen. Z.Y. et.al. [5], has taken Hill's general method to calculate the flow stress of a cylindrical specimen of AA6063 aluminum alloy under uniaxial simple compression and also to consider the friction effect at the die-specimen interface. Both the results of FEM analysis and compression test were combined to evaluate the friction coefficient.

Ramanathan. S. et.al [6], found out the optimum working regions and flow instable regions of 2124 Al alloy manufactured by powder metallurgy method, by using processing maps. They also found the power dissipation efficiency and instability parameters of the material.

Narayanasamy and Pandey studied the effect of barreling in aluminium solid cylinders during cold upsetting which most significantly pertains to the work to be done in this particular experimentation [7]. M. Oktay ALNIAK and Fevzi BED_IR et.al [8] have studied the Changes of Grain Sizes and Flow Stresses of AA2014 and AA6063 Aluminum Alloys at High Temperatures in Various Strain Rates.

Matruprasad Rout et.al[9] studied the flow stress and barreling behavior of aluminum alloy solid cylinder during upset forging at elevated temperature and found that flow stress, strain hardening exponent *n* and strength coefficient A all decreases with the increase in temperature and the radius value increases with the increase in test temperature and decreases with the increases in amount of strain.

Vaibhav Dash et. Al[10] has performed the bulging test of Aluminium billets (of hexagonal cross-section) under constant conditions of friction at room temperature and has found that with an increase in the percentage of height reduced the compressive load required shows an increasing trend with a rapid increase toward the end of compression and the bulging and barreling diameter of the specimen does not only depend on the height of the deformed specimen but also on the percentage reduction.

Chapter 3
Experimental Details

3. Experimental Details

3.1 Experimental Setup

The experiments were carried out in the universal testing machining of INSTRON SATEC 600 KN. 600 KN Models of INSTRON are ideal for high capacity tension, compression, flex and shear testing. These models feature an ultra large, single test space and so users can easily and safely load and unload specimens. This design offers the ultimate versatility by accommodating a large variety of specimen sizes, grips, fixtures and extensometers. Models include: 300KN, and 600KN, 1200KN, 1500KN, 2000KN and 3500KN.

3.1.1 INSTRON SATEC KN 600 Specifications

Followings are the specifications of the machine

Table 3. 1 Specifications of INSTRON SATEC 600 KN

maker	Instron,UK
type	hydraulic
software	Bluehill EM Console
Max. Loading capacity	600 KN
Max. Vertical test opening	1625 mm
Horizontal test opening	711 mm
Actuator stroke	508 mm
Max testing speed at full load	200 mm/min
Stiffness deflection	<1.0 mm
Load accuracy	±0.5% of reading down to 1/500 of Load cell capacity
Strain accuracy	±0.5 of reading down to 1/50 of Full range to ASTM E83 class B-1,B-2 0r ISO9513 class 0.05 extensometer
Position accuracy	±0.5% or 0.13 mm

Figure 3.1 INSTRON static

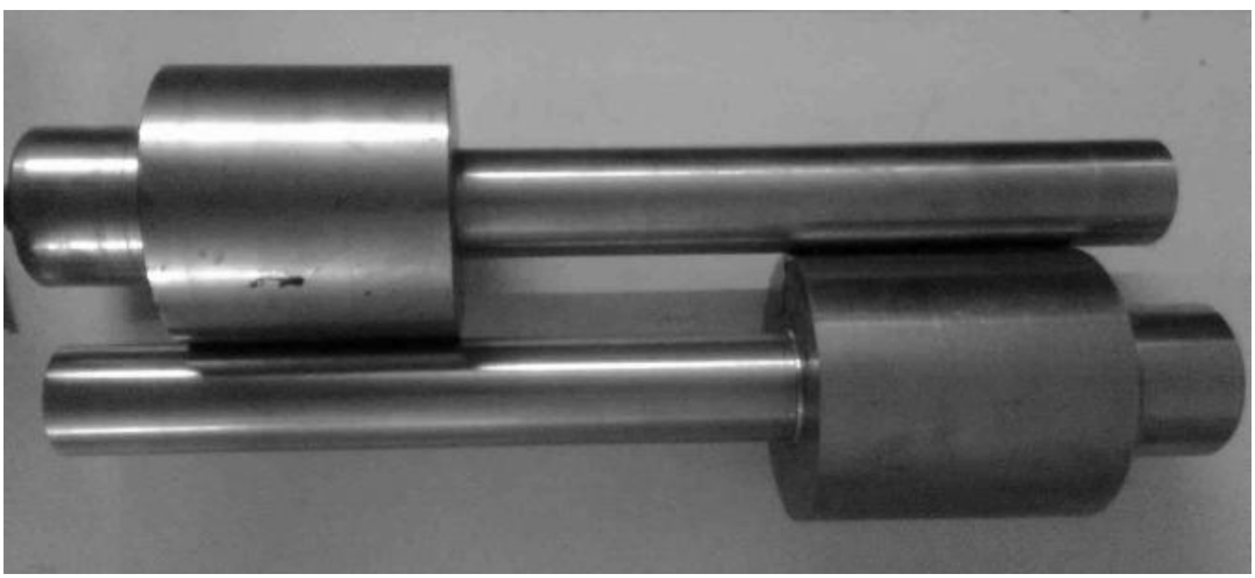

Fig 3.2 Figure 3. 3 Experimental set up for high temperature compression test

3.1.2 Furnace

It is an induction furnace having refractory ceramic fibre. These three zone resistance wire wound furnaces are of split construction to facilitate fast and easy loading of a pre-assembled specimen train. The case is constructed from stainless steel with aluminum and hardened insulation board end plates. The optional front cut-out allows the use of side-entry high-temperature extensometer. Adjustable stainless steel latches keep the furnace halves locked together during use, but are then easily opened once testing is complete. The furnace is available with optional heavy duty brackets or mountings, which attach to a wide range of testing systems. The resistance wire is wound on to recrystallized alumina tube in three independent zones to form the furnace element. This three-zone format allows the user to tailor the furnace temperature gradient, creating a uniform central zone. High-performance ceramic fiber insulation is used to reduce heat losses and provide fast heating rates.

Model and Style	SF- 16, 2230
Heat Zone Length	280 mm
No. of Zones	3
Element Resistance per Zone	17.6 Ohms
Furnace Length	330 mm
Furnace Outside Dia.	255 mm
Internal Bore Dia.	75 mm
Weight	21 Kg. (approx.)
Operating Temperature	1200°C
No. of Thermocouples	3
Thermocouples Type	K
Voltage	115 Vac.
Watt	2250 W, 750 W/ Zone
Phase	Single
Ampere	21 A, 6.52A/ Zone
Hertz	60 Hz/ 50 Hz
Temperature Controller	Type Eurotherm 2416
No. of Controller	3

Fig 3.3 furnace

Fig 3.4 temperature controller

3.1.3 Hydraulic Power Supply

Table 3. 3 Hydraulic Power Supply

Model	V22a
Height	1030 mm
Required Floor Space	(1220×935) mm
Weight	522 Kg. (approx.)
Required Flow at Maximum Testing Speed	12.37 Lpm
Ideal Pressure	28 bar
System Relief Pressure	179 bar
Motor Power	5 hp

3.2 Graphite as a lubricant:

Graphite is one of the allotropes of carbon. It is structurally composed of planes of polycyclic carbon atoms that are hexagonal in orientation. The distance of carbon atoms between planes is longer and therefore the bonding is weaker. Graphite is best suited for lubrication in a regular atmosphere. In an oxidative atmosphere graphite is effective at high temperatures up to 450ºC continuously and can withstand much higher temperature peaks. Graphite is characterized by two main groups, natural and synthetic. Graphite as a lubricant is used as dry powder or mixed with water or oil. When mixed with water, it is called 'aqua-dag' and when mixed with oil, it is called 'oil dag'. Graphite powder and machine oil in a proper ratio were mixed properly to form the lubricant for the test.

Graphite lubrication is used so that the specimen doesn't get forged to the anvil and ram at high temperature.

3.3 Specimen Preparation

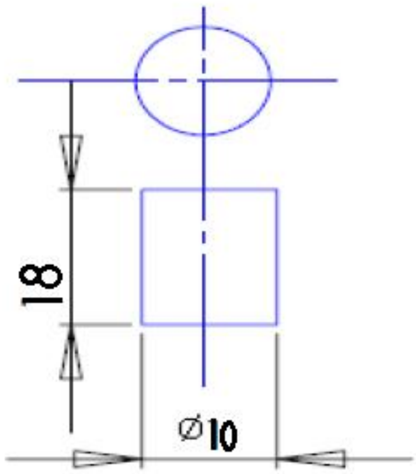

Fig 3.5 specimen

Compression Test to be conducted requires the testing of nine specimens prepared from the raw aluminium rod.

Specimen Specifications:

L/Deff ≈ 1.5 for to assure a geometrical dimensional factor and homogeneous deformation

L = Length of the Specimen

Deff = Effective Diameter of the Cross Section of the Specimen

Hence if Deff =10 mm, L should be approximately 15 mm

In the current experiment, L has been taken as 18 mm

Specimens of the required dimensions (figure 3.5) were cut from the aluminum alloy bar using hacksaw and filing operation was carried out to make the two ends parallel.

3.4 Description

After applying graphite lubricant coating on both the sides of the specimens, they are placed in between the top and bottom platen of the setup such that the axis of the cylindrical specimen is concentric with the axis of the ram. Furnace is now closed and the specimen is heated up to the desired temperature. Specimens are held on the testing temperature for 2-3 min after achieving the desired temperature to get well-proportioned and homogenous microstructure. Then hydraulic load is applied on the test specimen. The test is carried out at constant temperature. For each test temperature, one specimen was taken and deformed to different strain levels. The loads used during each deformation were recorded automatically by the BLUEHILL software incorporated with the UTM machine. Compressive test was carried out by giving a deformation of 10 mm, at a uniform strain rate of $0.001s^{-1}$ and at nine different temperatures of 35°C, 50°C, 75°C, 100^0C, 125°C, 150^0C, 175°C, 200^0C and 225^0C. At the end of each experiment time taken(sec), compressive extension(mm), compressive load(N), compressive stress(Pa), compressive strain(%), true stress(Pa) and true strain(%) were recorded automatically in the database of the computer, which was further used by the software to generate True stress vs. True strain graph .

Chapter 4
Results and Discussions

4 Result and Discussion

4.1 Flow curve (true stress vs. true strain)

Actually the metal continues to strain harden all the way, so that the stress required to produce further deformation should also increase. If the true stress based on the actual cross-sectional area of the specimen is used, it is found that stress-strain curve increases continuously until plastic deformation occurs. If the strain measurement is also based on instantaneous measurement, the curve is called true stress-strain curve. It is also known as flow curve, since It represents the basic plastics flow characteristics of the material. Many attempts have been made to fit mathematical equations to this curve. The most common is a power expression of the form

$$\sigma = A \times \varepsilon^{n} \quad \text{.......................................(1)}$$

Where , σ= true stress, A is strength coefficient, n is the strain hardening exponent

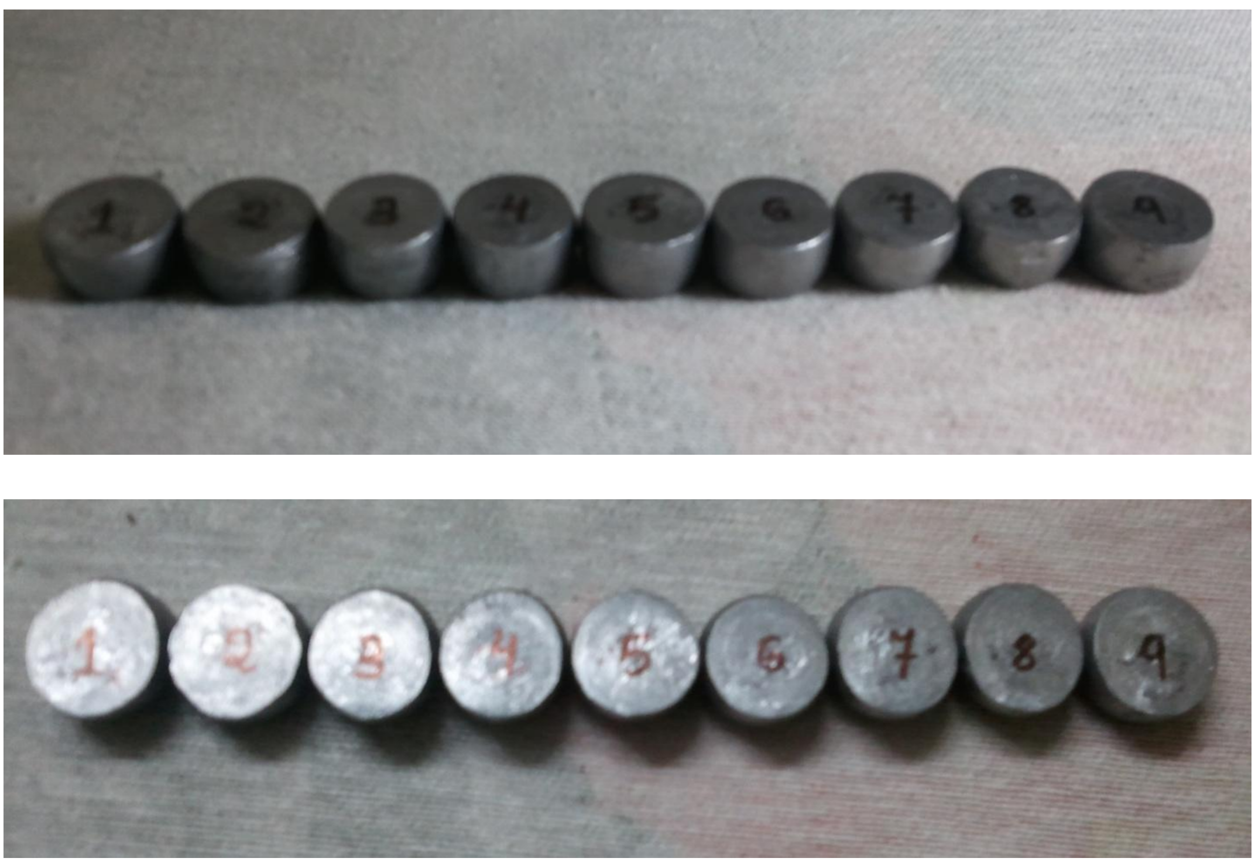

Fig 4.1 deformed specimens

BLUEHILL software incorporated with the UTM machine automatically generates the flow curve for each specimen instantaneously after the experiment using the true stress and true strain data saved in computer's database. It uses the engineering equation to generate the flow curves.

❖ <u>FOR TEMPERATURE -35^{o}C</u>

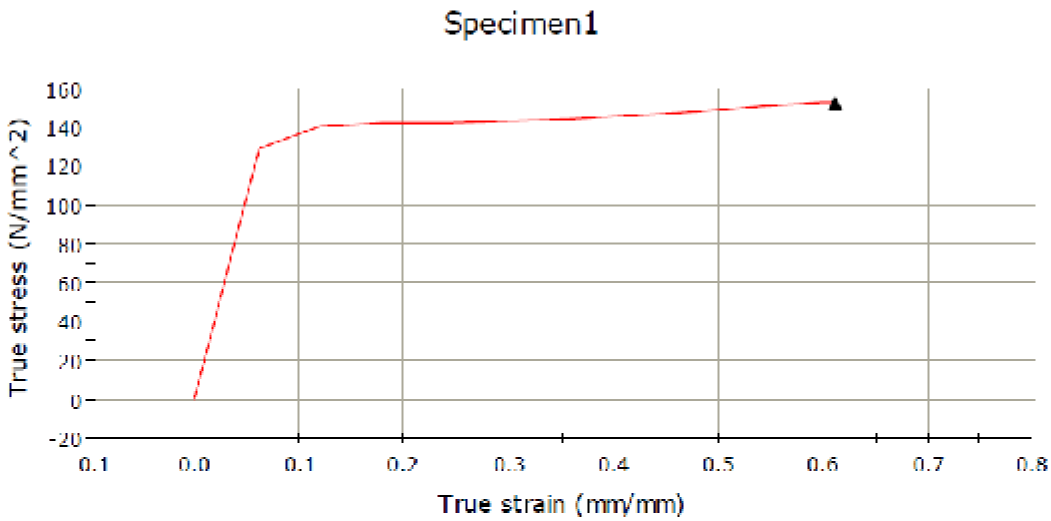

Fig 4.2 flow curve of specimen-1

❖ <u>FOR TEMPERATURE -50^{o}C</u>

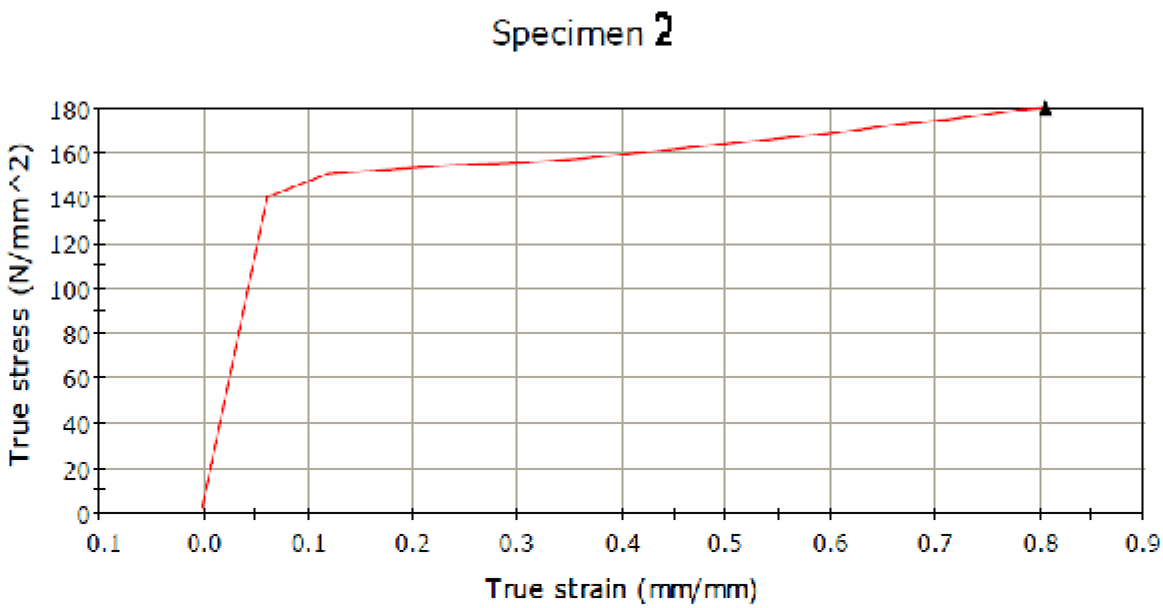

Fig 4.3 flow curve of specimen-2

❖ <u>FOR TEMPERATURE -75^{o}C</u>

Specimen-3

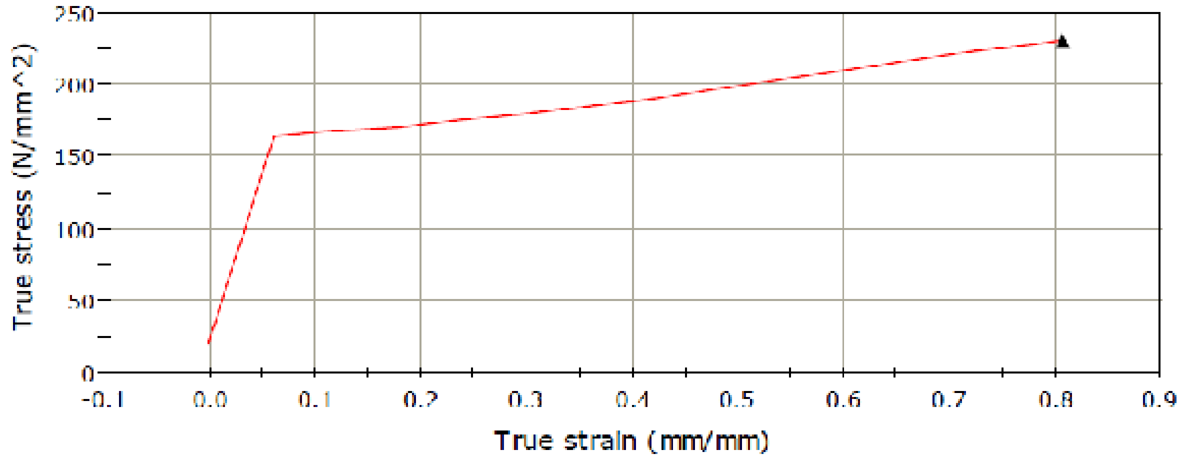

Fig 4.4 flow curve of specimen-3

❖ <u>FOR TEMPERATURE -100^{o}C</u>

Specimen-4

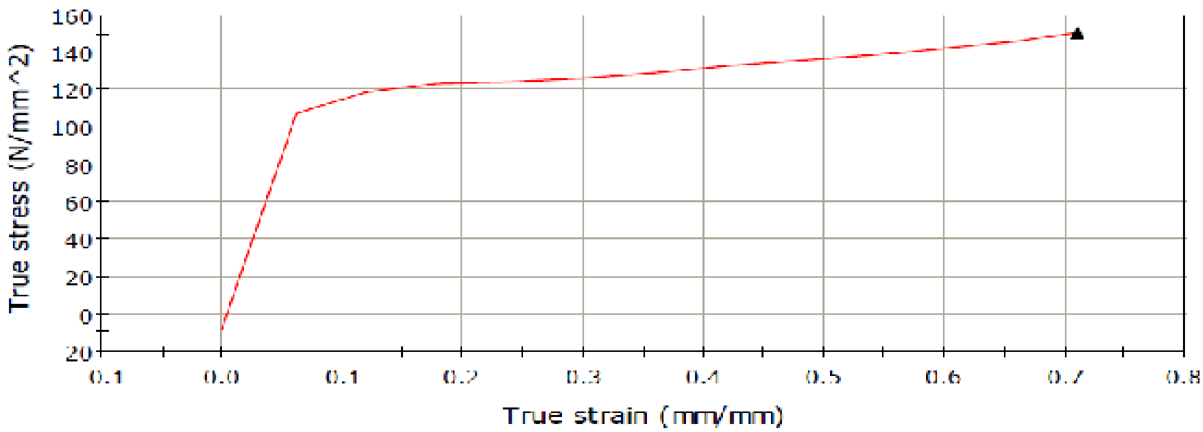

Fig 4.5 flow curve of specimen-4

❖ FOR TEMPERATURE -125^{o}C

Specimen-5

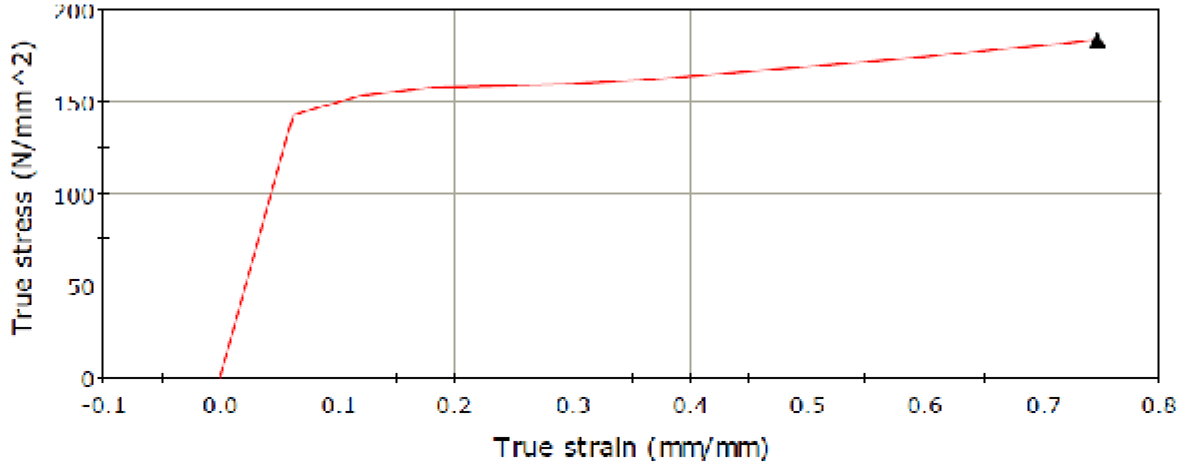

Fig 4.6 flow curve of specimen-5

❖ FOR TEMPERATURE -150^{o}C

Specimen-6

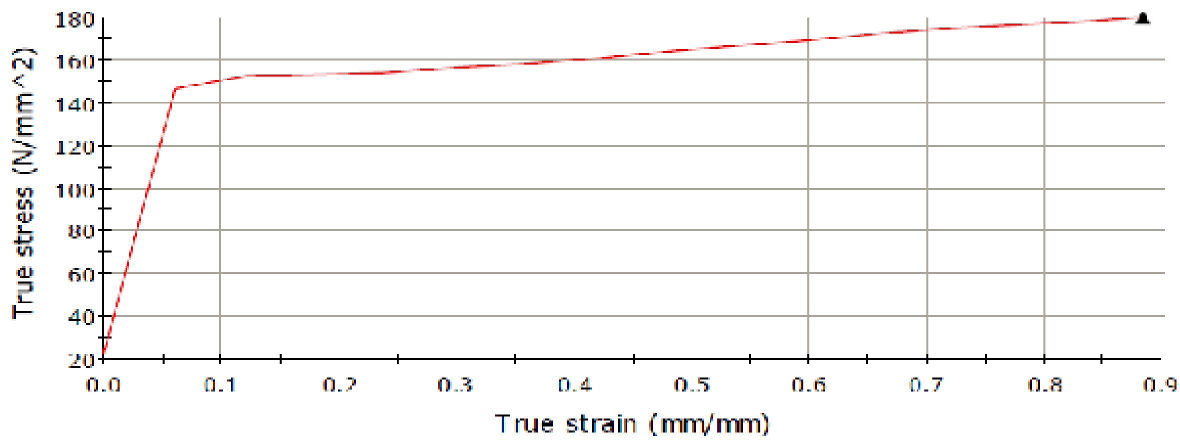

Fig 4.7 flow curve of specimen-6

❖ <u>FOR TEMPERATURE -175°C</u>

Specimen-7

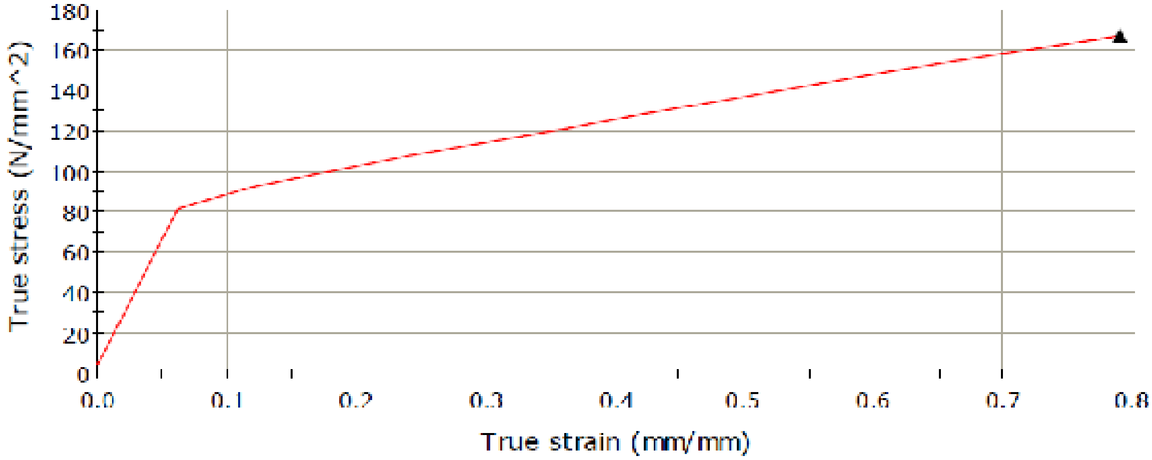

Fig 4.8 flow curve of specimen-7

❖ <u>FOR TEMPERATURE -200°C</u>

Specimen-8

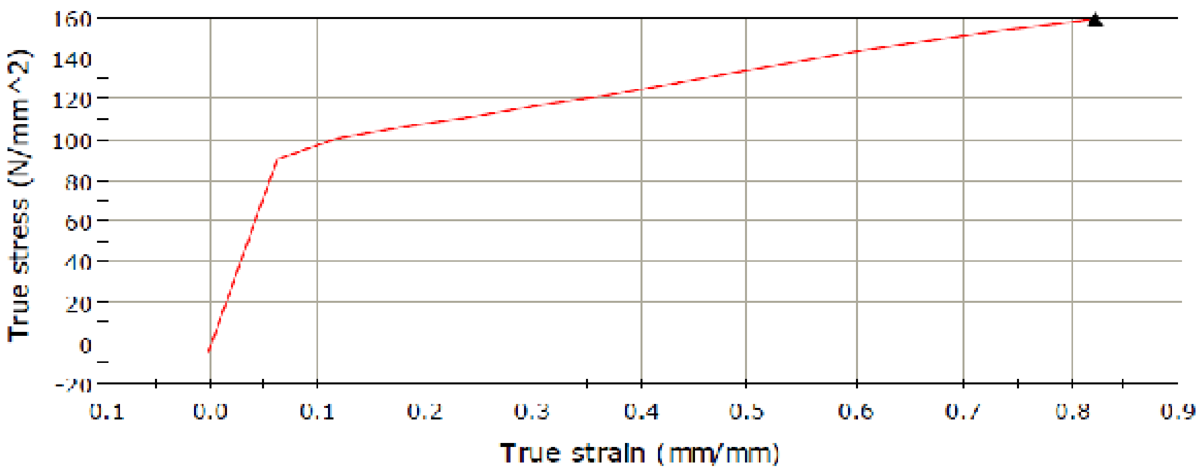

Fig 4.9 flow curve of specimen-8

❖ FOR TEMPERATURE -225°C

Specimen-9

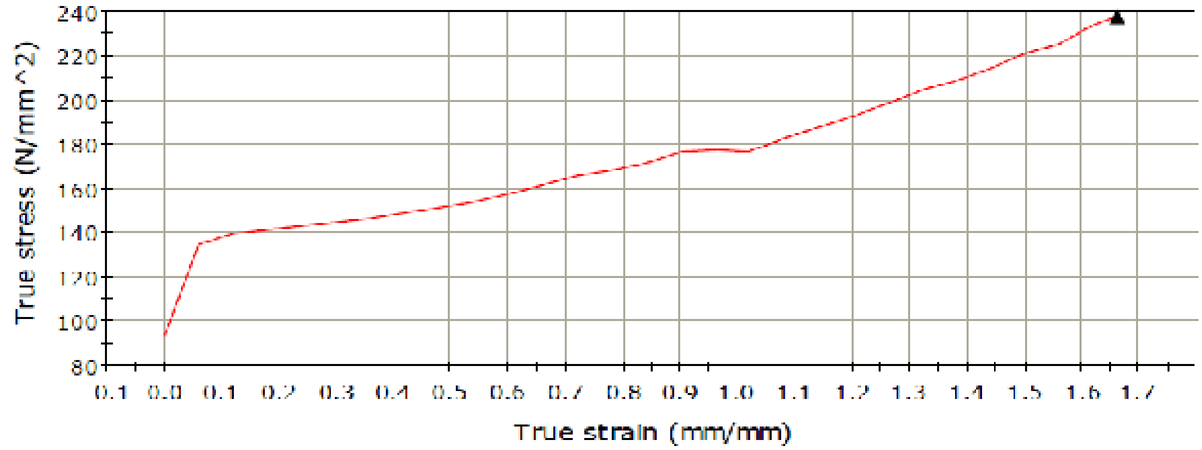

Fig 4.10 flow curve of specimen-9

Overall flow curve or True stress-strain curve for different Temperatures

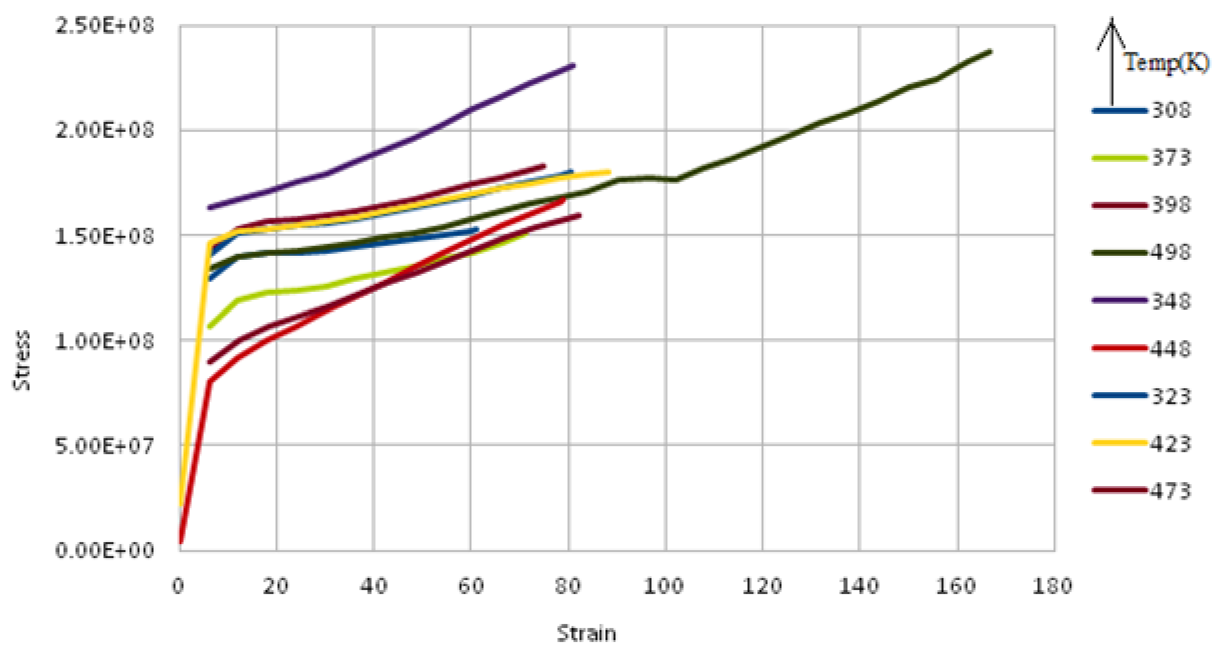

Fig 4.11 flow curve for different temperatures in kelvin

The figure shows the flow curve of the material at different temperatures. Data taken in regular interval during the experiment by the BLUEHILL software were taken to plot the flow curve. It was clear from the graph that the flow stress decreases with the increase in temperature, as the material get soften with the increase in temperature or flow-ability of the material increases.

4.2 Non linear least square regression analysis

Regression analysis is a technique used for modeling and analyzing variables, which establish mathematical relationship between a dependent variable and one or more independent variables. It demonstrates how the value of the dependent variable changes when any one of the independent variables is varied, while the other independent variables are held fixed. A large no of techniques have been developed for carrying out regression analysis. Out of all those**, linear regression** and **least squares regression** are more commonly used. Least squares problems fall into two categories: linear least squares and non-linear least squares, depending on the nature of variation of the dependent variable with the independent variables. The main difference between these two is linear least square has a closed-form solution where as the nonlinear has no closed-form solution and is usually solved by iterative refinement; at each iteration the system is approximated by a linear one.

The purpose of using Regression Analysis here is to establish a mathematical relationship between true stress and true strain, which will define the flow stress behaviour of the material. Many attempts have been made to fit mathematical equations to this curve. The most common is a power expression of the form

$$\sigma = A \times \varepsilon^{n} \quad \text{..(1)}$$

Taking natural logarithm on both the sides of eq^n-1, we get

$$\Rightarrow \ln(\sigma) = \ln A + n \times \ln(\varepsilon) \quad \text{................................(2)}$$

eq^n-2 represents the equation of a straight line (Y = C+ mX),which can be solved by linear regression analysis in order to find values of strength coefficient A and strain hardening exponent 'n' at different temperatures.

The following relationships have been determined by linear regression analysis with the help of **MINITAB** software.

❖ **Temperature-35°C: (specimen-1)**

$$\ln(\sigma) = 18.6 + 0.0620 \ln(\mathcal{E}$$

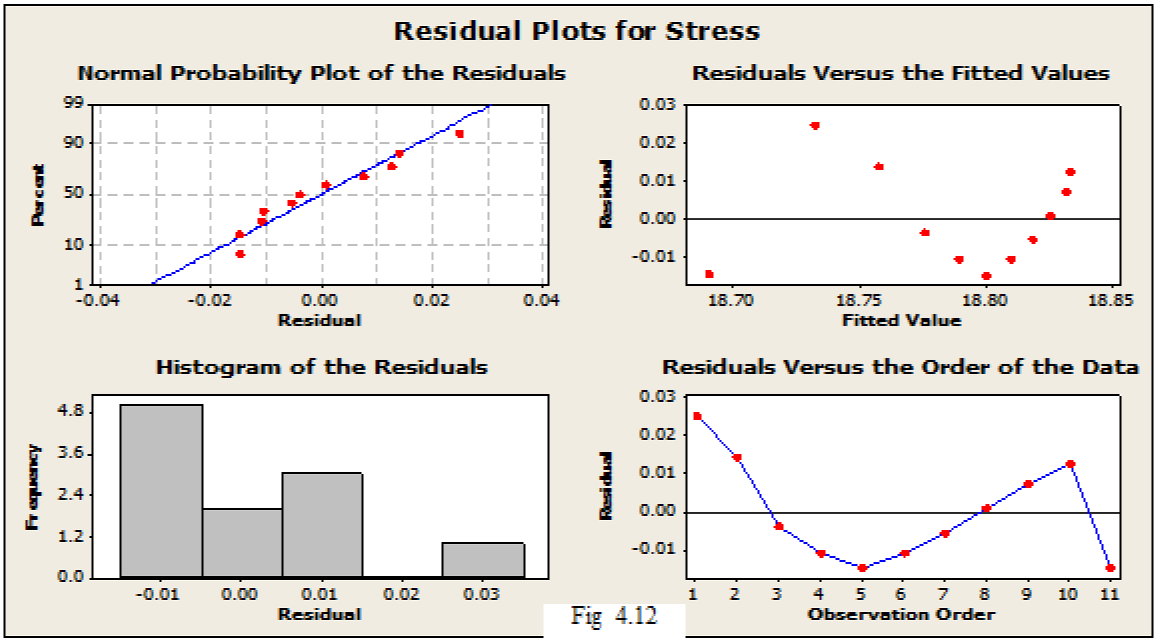

Fig 4.12

❖ **Temperature-50°C: (specimen-2):**

$$\ln(\sigma) = 18.6 + 0.0884 \ln(\mathcal{E})$$

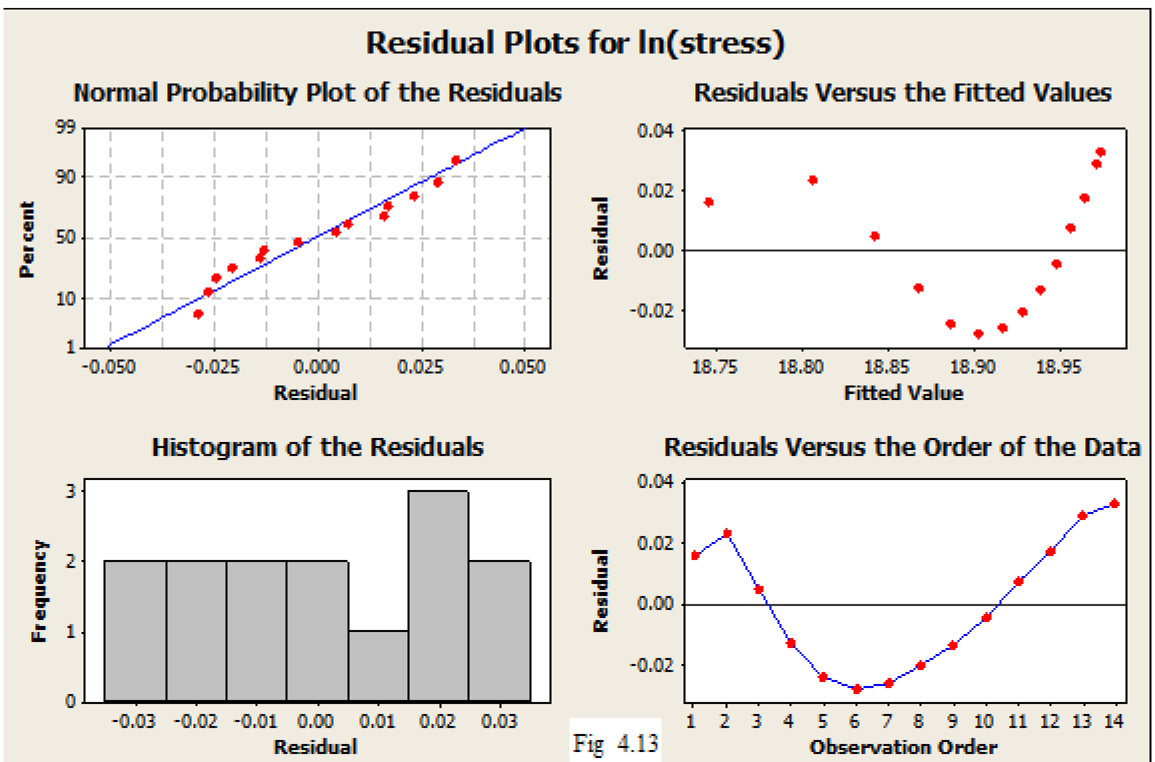

Fig 4.13

- **Temperature-75°C: (specimen-3) :**

$$\ln(\sigma) = 18.6 + 0.144 \ln(\mathcal{E})$$

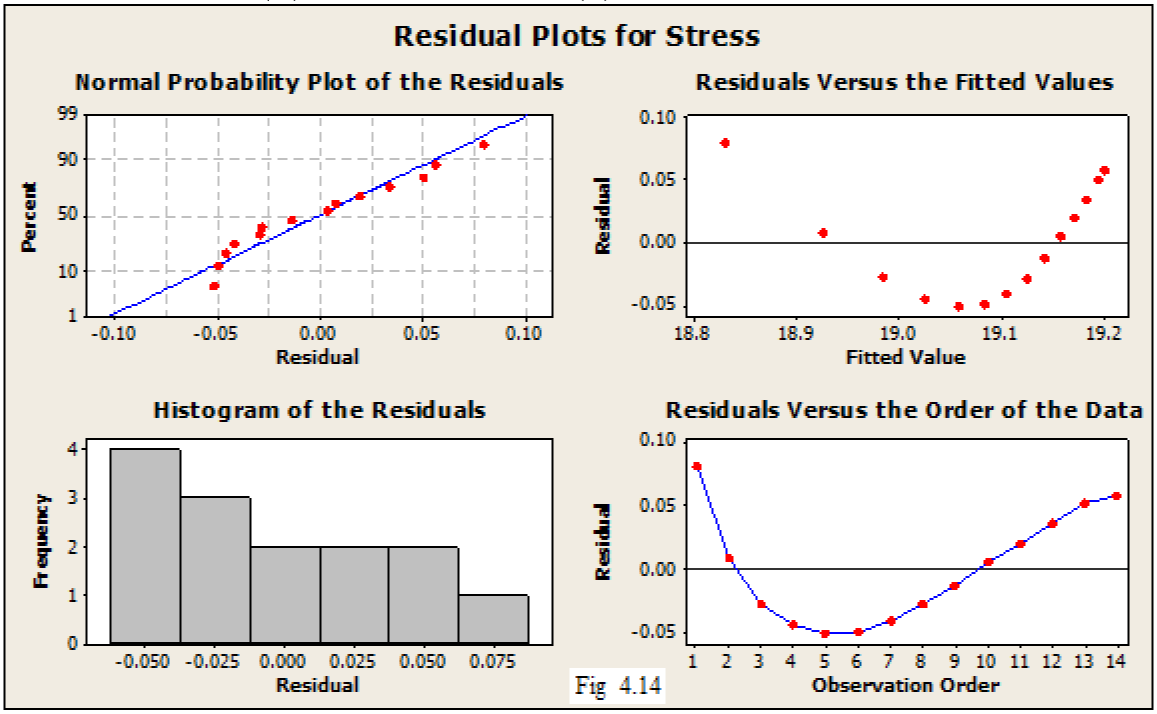

Fig 4.14

- **Temperature-100°C: (specimen-4)**

$$\ln(\sigma) = 18.3 + 0.124 \ln(\mathcal{E})$$

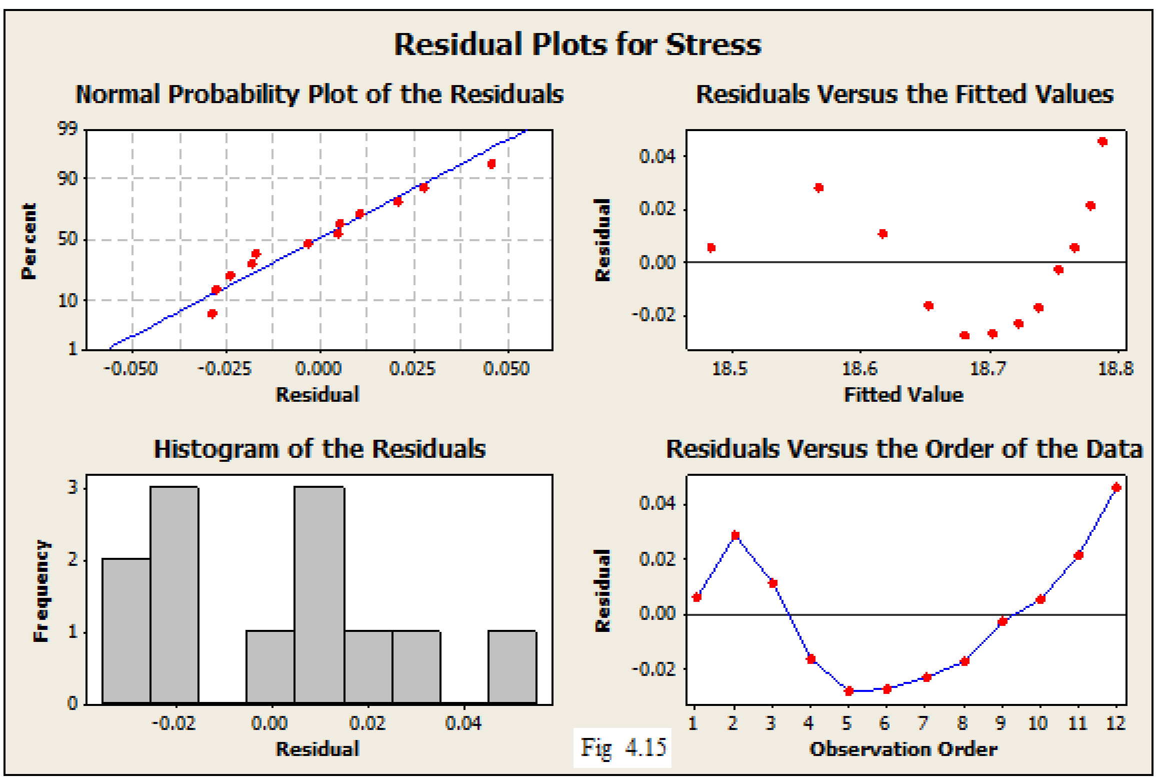

Fig 4.15

❖ **Temperature-125°C: (specimen-5)**

$$\ln(\sigma) = 18.6 + 0.0926 \ln(\mathcal{E})$$

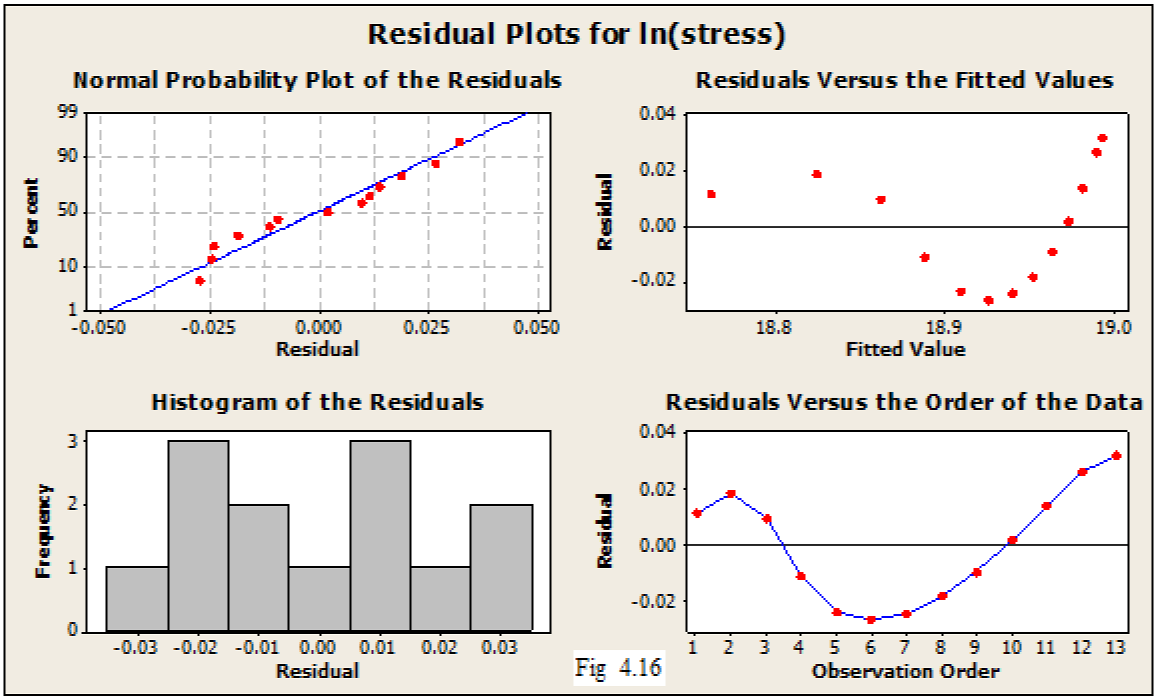

Fig 4.16

❖ **Temperature-150°C: (specimen-6)**

$$\ln(\sigma) = 18.6 + 0.0796 \ln(\mathcal{E})$$

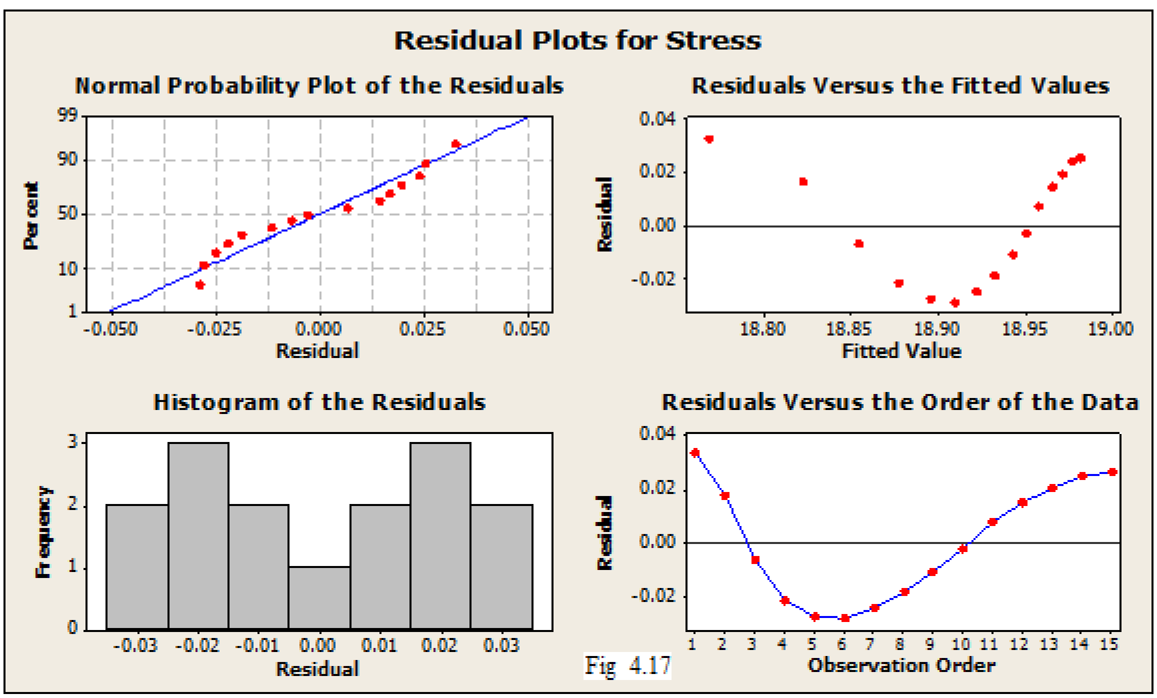

Fig 4.17

❖ **Temperature-175°C: (specimen-7)**

$$\ln(\sigma) = 17.6 + 0.295\ \ln(\mathcal{E})$$

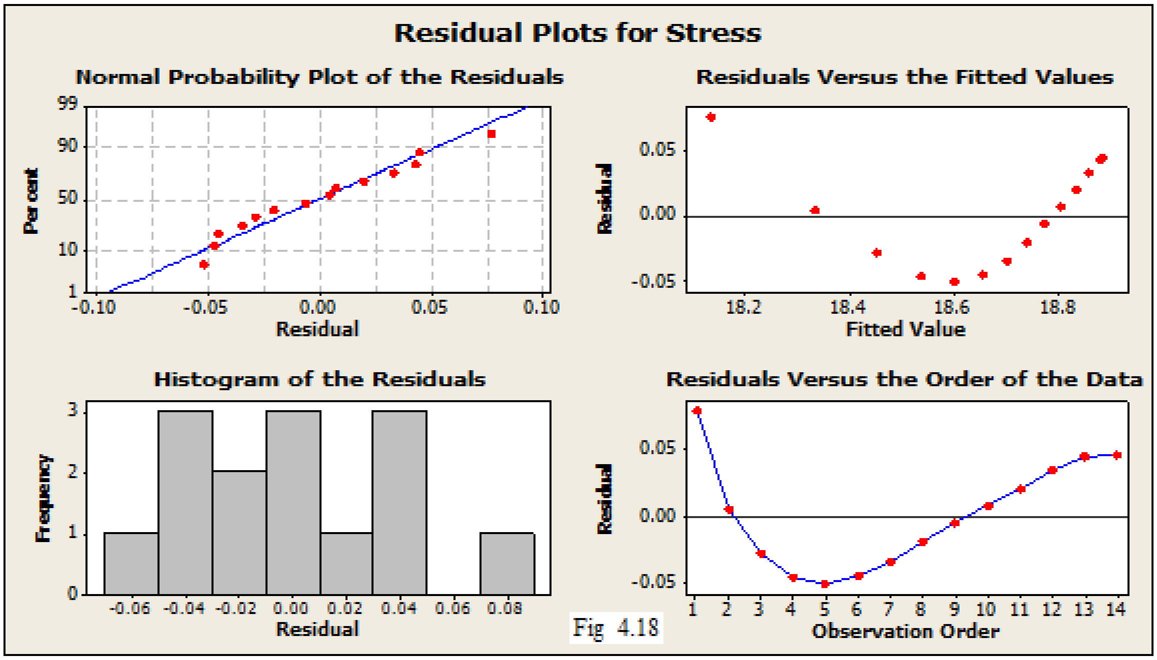

Fig 4.18

❖ **Temperature-200°C: (specimen-8)**

$$\ln(\sigma) = 17.8 + 0.227\ \ln(\mathcal{E})$$

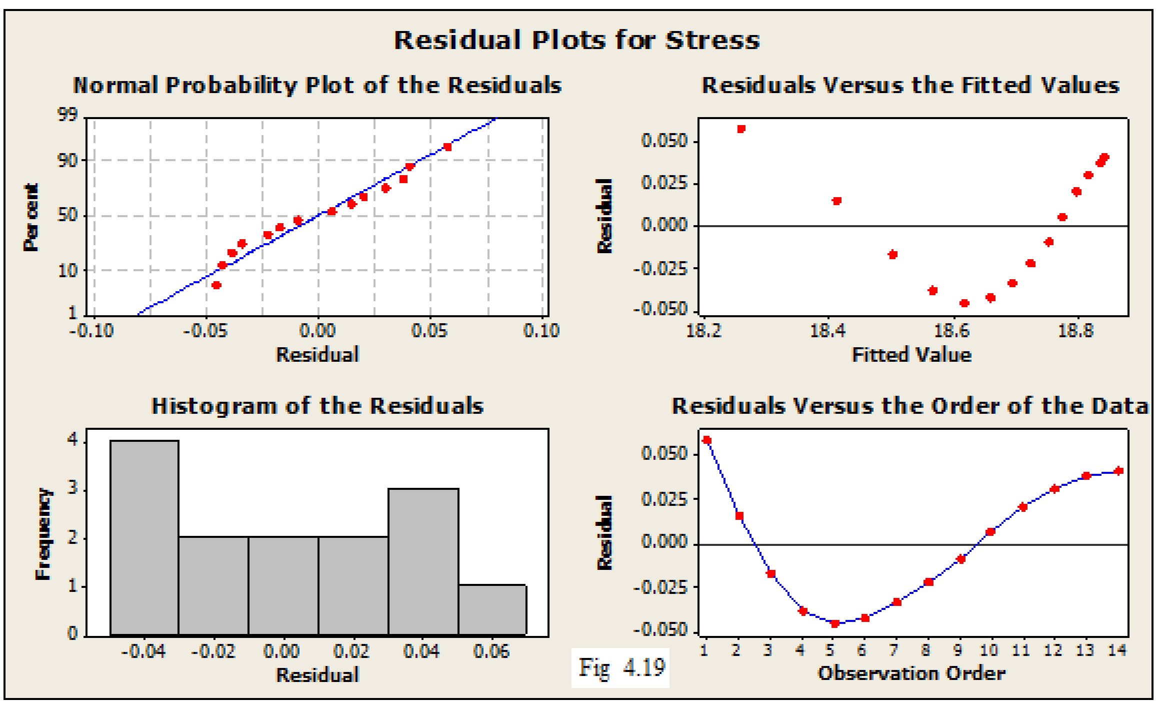

Fig 4.19

- **Temperature-225°C: (specimen-9)**

$$\ln(\sigma) = 18.2 + 0.179 \ln(\varepsilon)$$

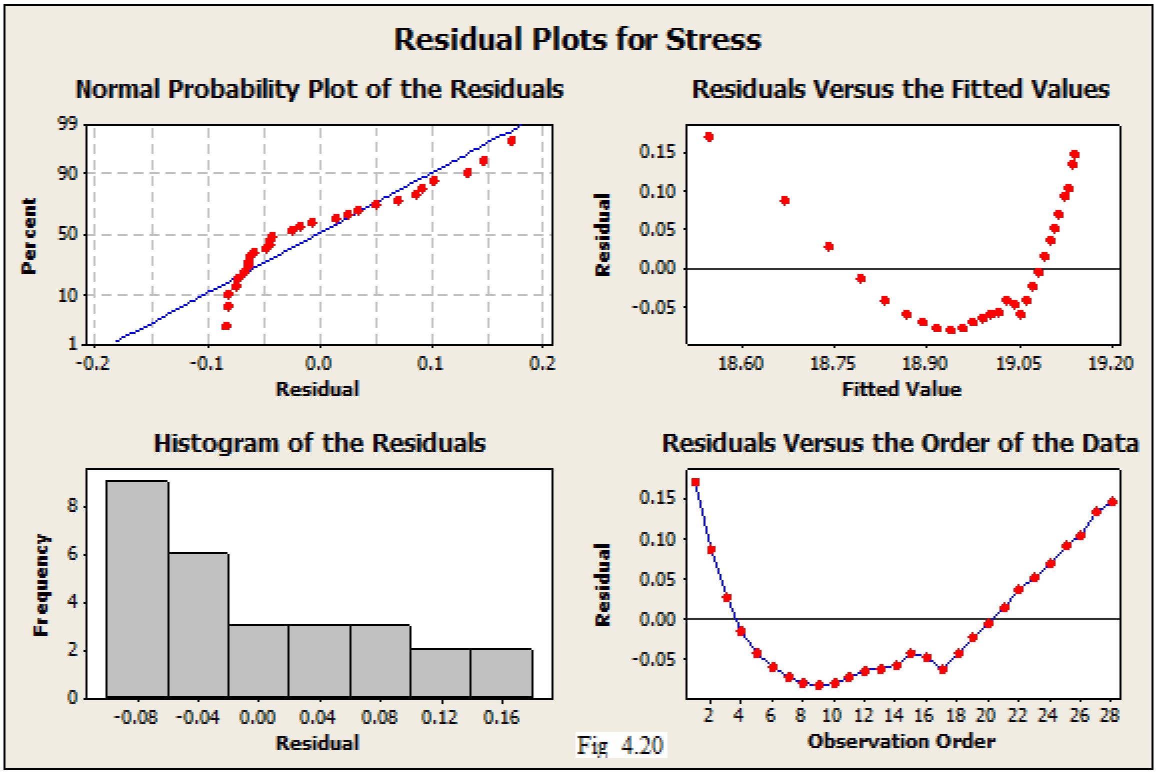

Fig 4.20

From above nine number of equations, we can easily find the strength coefficient A simply by taking exp{ln(A)}.The strength coefficients A and strain hardening coefficients 'n' for different temperatures have been tabulated below:-

A	n	T(K)
119640264	0.062	308
119640264	0.0884	323
119640264	0.144	348
88631688	0.124	373
119640264	0.9626	398
119640264	0.0796	423
44013194	0.295	448
53757836	0.227	473
80197267	0.179	498

Table 4.1

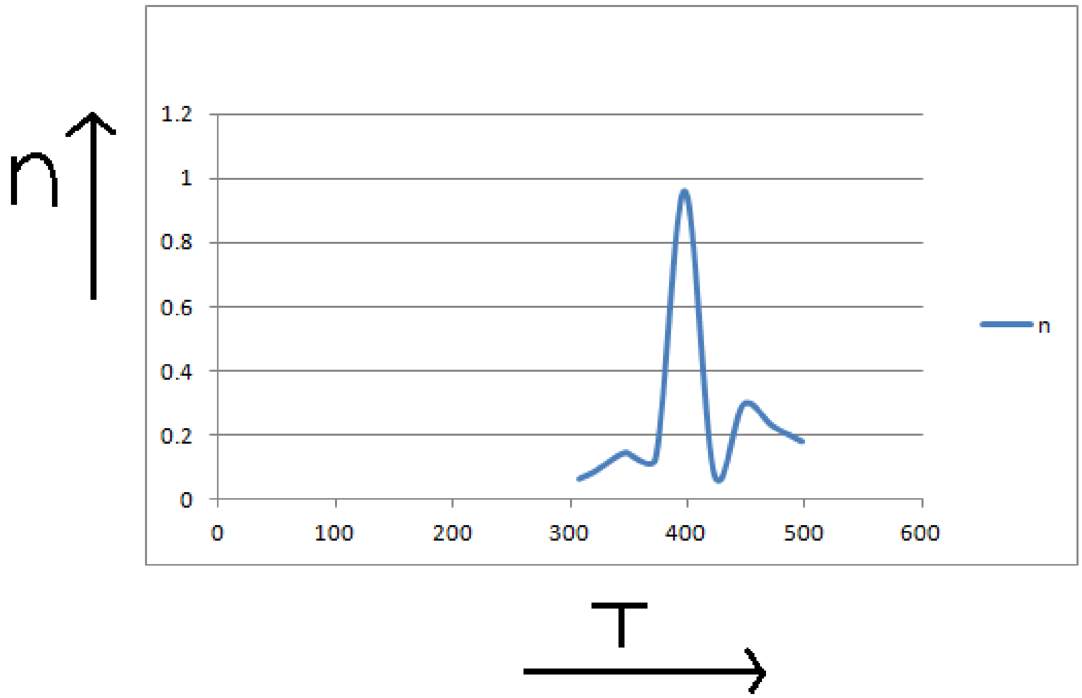

Fig 4.21 n vs.T (kelvin)

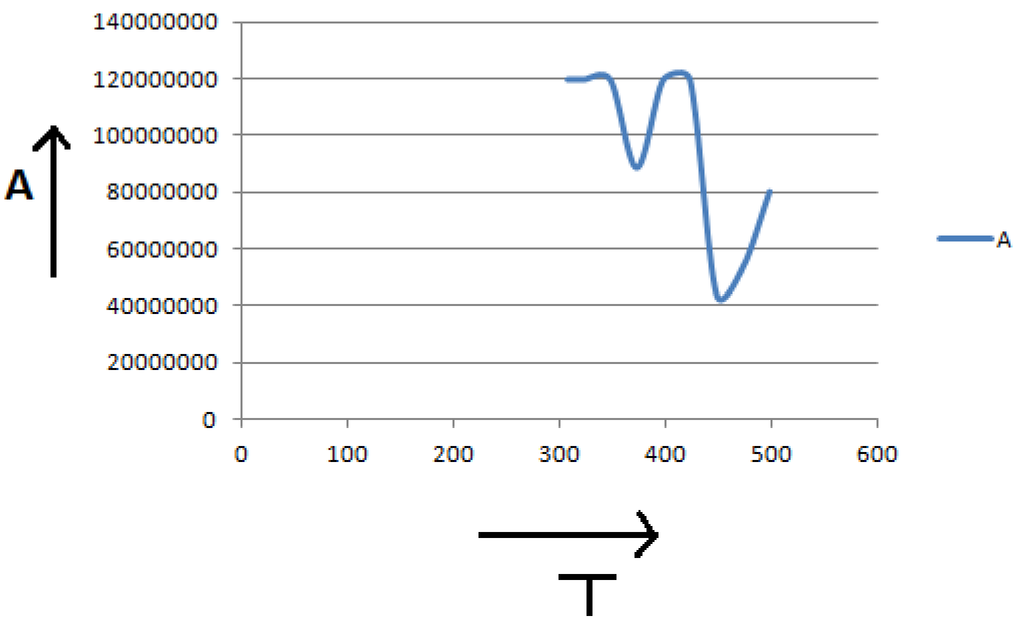

Fig 4.22 A vs. T(kelvin)

4.3 Behaviour of flow curve at different temperatures:

Our objective is to establish a single mathematical relationship among true stress, true strain and temperature, which will show the flow stress behaviour of the material at different temperature ranges.

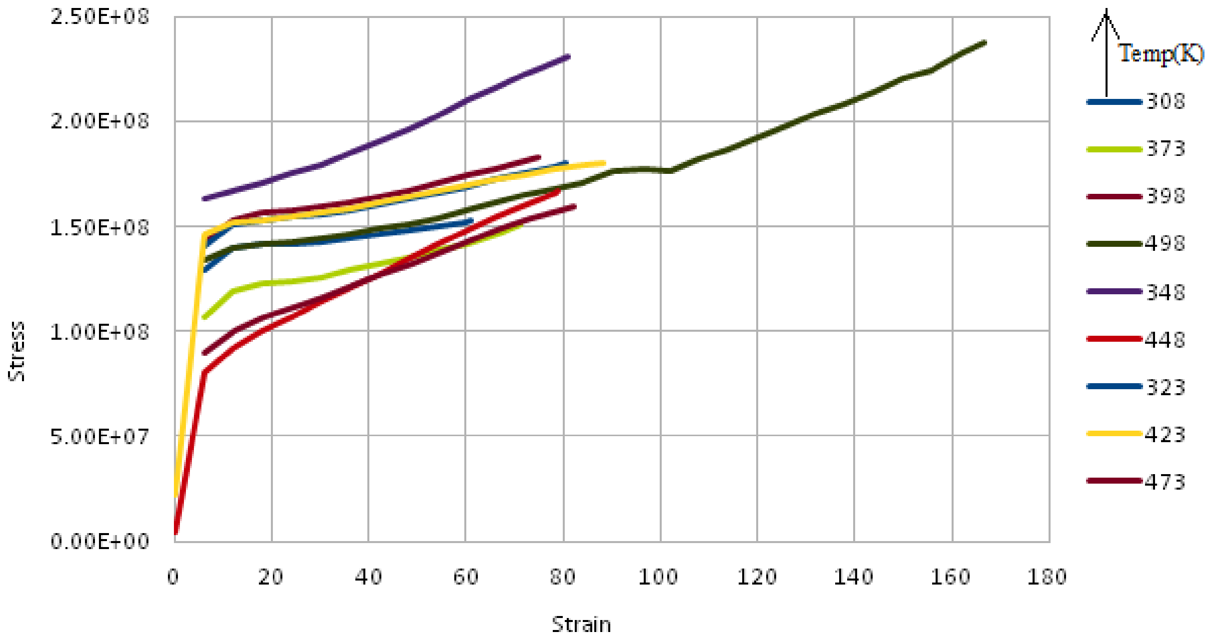

Fig 4.23 (flow curve at different temperatures in Kelvin)

We are looking to obtain a relation that will precisely describe the characteristics of flow curves in the above figure at corresponding temperatures,which will have following form:-

$$\sigma = A \times \varepsilon^{n} \times T^{k} \text{.......................................(3)}$$

Taking natural logarithm on both the sides of eq^{n}-1, we get

$$\Rightarrow \ln(\sigma) = \ln A + n \times \ln(\varepsilon) + k \times \ln(T) \text{...........................(4)}$$

Again using linear regression analysis using MINITAB, we obtain following equation:

$$\ln(\text{Stress}) = 19.9 + 0.186 \ln(\text{Strain}) - 0.281 \ln(\text{Temperature})$$

$$\Rightarrow \qquad \sigma = \frac{19.9 \times (\varepsilon)^{0.186}}{T^{0.281}}$$

................Eq^n-3

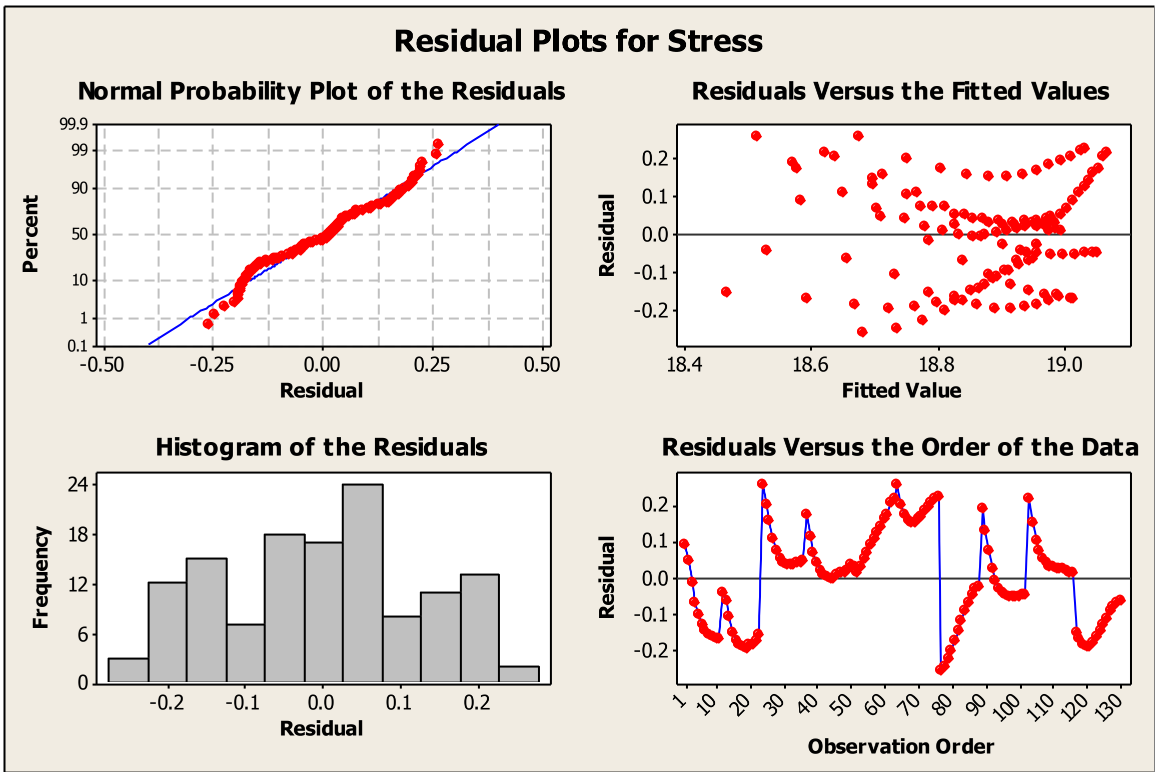

Fig 4.24 regression analysis

Chapter 5
Conclusions

5. Conclusions

Following conclusions were made from the above work:

(1)True stress or flow stress increases with increasing true strain.
(2) True stress decreases with increasing temperature.
(3) Strain hardening exponent n found increasing and then decreasing with increase in temperature and strength coefficient A decreases with the increase in temperature.
(4) The true stress, true strain and temperature can be correlated by the following empirical formula

$$\sigma = \frac{19.9 \times (\varepsilon)^{0.186}}{T^{0.281}}$$

Where σ= true stress
ε=true strain
T=temperature in Kelvin

6. Reference

[1] Jin Nengping. et. al Hot deformation behavior of 7150 aluminum alloy during compression at elevated temperature, Journal of Materials characterization 60 (2009)530-536.

[2] Zhang Hui et.al, Hot deformation behavior of the new Al-Mg-Si-Cu aluminum alloy during compression at elevated temperatures, Journal of Materials characterization58 (2007) 168-173.

[3] Xiu-yu WEI. et.al, Flow stress of 2197 Al-Li alloy during hot compression deformation, Transaction of non ferrous metals society of China 17 (2007) s280-s284.

[4] Aluko. O. et.al, Warm Compression Tests of Aluminum Alloy, Journal of Materials Engineering and Performance 7 (1998) 474-478.

[5] Chen. Z.Y. et.al. Deformation Behavior of Aa6063 Aluminium Alloy After Removing Friction Effect under Hot Working Conditions, Acta Metall. Sin. (Engl. Lett.) Vol.21 No.6 (2008) 451-458.

[6] Ramanathan. S. et.al. Hot Deformation Behavior of 2124 Al Alloy, Journal of Material Science Technology, Vol.22 No.5, (2006) 611-615.

[7]. Narayanasamy R, Pandey KS (1997) Phenomenon of barreling in Al solid cylinders during cold upset-forging. J Mater Proc Tech 70: 17–27

[8]]. M. Oktay ALNIAK and Fevzi BED_IR et.al. The Changes of Grain Sizes and Flow Stresses of AA2014 and AA6063 Aluminum Alloys at High Temperatures in Various Strain Rates. Turkish J. Eng. Env. Sci.27 (2003) , 59 { 64.

[9]Matruprasad Rout et.al. The flow stress and barreling behavior of aluminum alloy solid cylinder during upset forging at elevated temperature. Department of Mechanical Engineering,National Institute of Technology,Rourkela.2011

[10]Vaibhav Dash et. Al. The bulging test of Aluminium billets (of hexagonal cross-section) under constant conditions of friction at room temperature**.** Department of Mechanical Engineering,National Institute of Technology,Rourkela.2011

[11] http://www.instron.us/wa/home/default_en.aspx